

(19) World Intellectual Property Organization  
International Bureau(43) International Publication Date  
7 December 2006 (07.12.2006)

PCT

(10) International Publication Number  
WO 2006/130797 A2

(51) International Patent Classification: Not classified

(21) International Application Number:  
PCT/US2006/021343

(22) International Filing Date: 31 May 2006 (31.05.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
60/686,518 31 May 2005 (31.05.2005) US(71) Applicant (for all designated States except US): THE  
GENERAL HOSPITAL CORPORATION [US/US]; 55  
Fruit Street, Boston, MA 02114 (US).

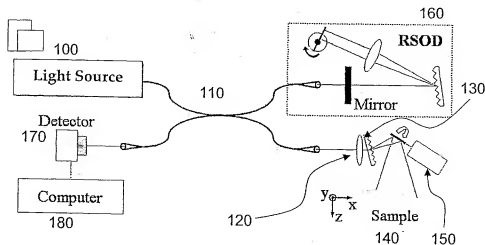
(72) Inventors; and

(75) Inventors/Applicants (for US only): BOUMA, Brett,  
Eugene [US/US]; 12 Monmouth Street, Quincy, MA  
02171 (US). TEARNEY, Guillermo, J. [US/US]; 12  
Fairmont Street, Cambridge, MA 02139 (US). YELIN,  
Dvir [IL/US]; 76 Saint Paul Street, Brookline, MA 02446  
(US). YUN, Seok-hyun [KR/US]; 30 Cambridge Park  
Drive, Apt. 4128, Cambridge, MA 02140 (US).(74) Agent: ABELEV, Gary; DORSEY & WHITNEY LLP,  
250 Park Avenue, New York, NY 10177 (US).(81) Designated States (unless otherwise indicated, for every  
kind of national protection available): AE, AG, AL, AM,  
AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN,  
CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI,  
GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE,  
KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV,  
LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI,  
NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG,  
SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US,  
UZ, VC, VN, YU, ZA, ZM, ZW.(84) Designated States (unless otherwise indicated, for every  
kind of regional protection available): ARIPO (BW, GH,  
GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,  
ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),  
European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI,  
FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT,  
RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA,  
GN, GQ, GW, ML, MR, NE, SN, TD, TG).

## Published:

— without international search report and to be republished  
upon receipt of that reportFor two-letter codes and other abbreviations, refer to the "Guidance  
Notes on Codes and Abbreviations" appearing at the beginning  
of each regular issue of the PCT Gazette.

(54) Title: SYSTEM, METHOD AND ARRANGEMENT WHICH CAN USE SPECTRAL ENCODING HETERODYNE INTERFEROMETRY TECHNIQUES FOR IMAGING



(57) Abstract: Systems, arrangements and methods for obtaining three-dimensional imaging data are provided. For example, a broadband light source can provide a particular radiation. A first electro-magnetic radiation can be focused and diffracted, and then provided to at least one sample to generate a spectrally-encoded line. A second electro-magnetic radiation may be provided to a reference, which may include a double-pass rapidly-scanning optical delay, where the first and second electro-magnetic radiations can be based on the particular radiation. An interference between a third electro-magnetic radiation (associated with the first electro-magnetic radiation) and a fourth electro-magnetic radiation (associated with the second electro-magnetic radiation) can be detected. The spectrally-encoded line may be scanned over the sample in a direction approximately perpendicular to the line. Image data containing three-dimensional information can then be obtained based on the interference. The exemplary imaging methods and systems can be used in a small fiber optic or endoscopic probe.

**SYSTEM, METHOD AND ARRANGEMENT WHICH CAN USE  
SPECTRAL ENCODING HETERODYNE INTERFEROMETRY  
TECHNIQUES FOR IMAGING**

CROSS-REFERENCE TO RELATED APPLICATION

- 5           This application is based upon and claims the benefit of priority from U.S. Patent Application Serial No. 60/686,518, filed May 31, 2005, the entire disclosure of which is incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

- 10           Development of the present invention was supported in part by the U.S. Government under National Science Foundation grant BES-0086709. Thus, the U.S. Government may have certain rights in the invention.

FIELD OF THE INVENTION

- 15           The present invention relates to optical imaging and, more particularly, to systems, methods and arrangements that can use spectral encoding heterodyne interferometry techniques for imaging at least one portion of a sample.

BACKGROUND OF THE INVENTION

- Three-dimensional ("3D") endoscopy can assist with a variety of minimally invasive procedures by providing clinicians with depth information. Achieving depth-resolved imaging having a large, three-dimensional field of view can be difficult when small diameter flexible imaging probes such as, e.g., borescopes, laparoscopes, and endoscopes are utilized. The use of confocal imaging through a fiber-bundle using a high numerical aperture lens may be one technique that can be used to address this problem. Such technique is described in, e.g., Y. S. Sabharwal et al., "Slit-scanning confocal microendoscope for high-resolution in vivo imaging," Appl. Opt. 38, 7133 (1999). A 3D field of view for such devices, however, may be limited to less than a few millimeters due to a small clear aperture of the objective lens and a low f-number that may be required for high-resolution optical sectioning.
- 25           Other techniques such as, for example, stereo imaging and structured illumination have also been proposed for obtaining 3D endoscopic images. Such

techniques are described in, e.g., M. Chan et al., "Miniaturized three-dimensional endoscopic imaging system based on active stereovision," Appl. Opt. 42, 1888 (2003); and D. Karadaglic et al., "Confocal endoscope using structured illumination," Photonics West 2003, Biomedical Optics, 4964-34, respectively. These techniques may, however, require more components to construct a probe than would be required for confocal imaging that is performed using a fiber bundle. This additional hardware can increase the size, cost, and complexity of such devices.

Spectrally-encoded endoscopy ("SEE") techniques can utilize a broadband light source and a diffraction grating to spectrally encode reflectance across a transverse line within a sample. For example, a two-dimensional image can be formed by slowly scanning this spectrally-encoded line. This technique can be performed using a single optical fiber, thereby enabling imaging through a flexible probe having a small diameter. In particular, SEE images can have a larger number of resolvable points, and may be relatively free from pixilation artifacts as compared with images obtained using fiber-bundle endoscopes.

When combined with interferometry techniques and systems, SEE can provide three-dimensional images. A depth-resolved imaging can be achieved, e.g., by incorporating a SEE probe into a sample arm of a Michelson interferometer. Using such an arrangement, two-dimensional ("2D") speckle patterns can be recorded using a charge-coupled device ("CCD") camera at multiple longitudinal locations of a reference mirror. Subsequently, depth information can be extracted by comparing interference signals obtained at consecutive reference mirror positions. When using this technique, the reference mirror can be held stationary to within an optical wavelength while a single image (or line) is being acquired to avoid the loss of fringe visibility. Scanning a reference mirror that is positioned with such accuracy over multiple discrete depths can be very difficult at the high rates required for real-time volumetric imaging.

#### OBJECTS AND SUMMARY OF THE INVENTION

One of the objects of the present invention is to overcome certain deficiencies and shortcomings of the prior art systems (including those described herein above), and to provide exemplary SEE techniques, systems and arrangements

that are capable of generating three-dimensional image data associated with a sample. Exemplary embodiments of the present invention can provide methods, systems and arrangements that are capable of generating high-speed volumetric imaging of a sample. Exemplary embodiments of these systems and arrangements can be provided within the confines of a fiber optic probe or an endoscopic probe.

In certain exemplary embodiments of the present invention, a system can be provided that includes a light source or another electro-magnetic radiation generating arrangement. The light source can be a broadband source capable of providing the electro-magnetic radiation. The exemplary embodiment of the system can include a beam splitter configured to separate radiation from the light source into a first radiation and a second radiation. The system can be configured to direct the first radiation toward a sample. The first radiation can pass through a lens-grating arrangement (that can include a diffraction grating and a lens) to focus, modify and/or direct the first radiation. The lens-grating system can be configured to direct a spectrally-encoded line associated with the first radiation towards the sample. A scanning mechanism can also be provided that is configured to effectuate the scanning of the line over at least a portion of the sample in a direction that is approximately perpendicular to the line. A third radiation can be generated based on interactions between at least a portion of the spectrally-encoded line and the sample. The lens-grating arrangement and/or the scanning mechanism may be provided, e.g., in a probe. The probe may include an endoscope and/or a catheter.

The exemplary embodiment of the system can further include a rapidly-scanning optical delay ("RSOD") arrangement, where the second radiation can be configured to pass through the RSOD arrangement and possibly be affected thereby to generate a fourth radiation. A detection arrangement can also be provided that is configured to detect an interference between the third and fourth radiations. This detection arrangement can include, e.g., a charge-coupled device that is capable of generating raw data based on the interference.

A processing arrangement such as, e.g., a computer and/or a software arrangement executable by the processing arrangement, can be provided that is/are configured to generate the image data based on the detected interference between the third and fourth radiations. The processing arrangement and/or the software

arrangement can be configured to apply, for example, a Fourier transform to the raw data to generate the image data. A display arrangement can also be provided to display the images of at least one portion of the sample based on the image data. These images can optionally be displayed in real time, e.g., while the first radiation is being directed towards the sample.

In further exemplary embodiments of the present invention, a method can be provided for generating three-dimensional image data of at least a portion of the sample. A particular radiation can be provided which may include a first radiation directed to the sample and a second radiation directed to a reference. For example, the first radiation can be directed through a lens and a diffraction grating to provide a spectrally-encoded line directed towards the sample. This line can be scanned over at least a portion of the sample in a direction approximately perpendicular to the line. A third radiation can be produced based on an interaction between the first radiation and the sample. A fourth radiation can be generated by directing the second radiation through a rapidly-scanning optical delay.

An interference can then be detected between the third radiation and the fourth radiation. This interference can be used to generate three-dimensional image data that characterizes at least one portion of the sample. The image data can be used to display images of the sample on a display.

These and other objects, features and advantages of the present invention will become apparent upon reading the following detailed description of embodiments of the invention, when taken in conjunction with the appended claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Further objects, features and advantages of the invention will become apparent from the following detailed description taken in conjunction with the accompanying figures showing illustrative embodiments of the invention, in which:

Figure 1 is a block diagram of an exemplary embodiment of a time-domain spectrally-encoded imaging system according to the present invention;

Figure 2 is a diagram of an exemplary technique that may be used to extract both transverse and depth information from an interference trace using a short-

time Fourier transform in accordance with certain exemplary embodiments of the present invention;

Figure 3A shows an exemplary image of a fingertip obtained using a method, system and arrangement in accordance with exemplary embodiments of the present invention;

Figure 3B shows an exemplary image of the fingertip shown in Figure 3A in which depth information is superimposed using contour lines;

Figure 4A is an image of a surface of a quarter dollar coin obtained using a method, system and arrangement in accordance with exemplary embodiments of the present invention;

Figure 4B is an image of a surface of a dime placed 2.4mm in front of the quarter dollar coin shown in Figure 4A;

Figure 4C is an exemplary two-dimensional integrated image of the two coins shown in Figures 4A and 4B, which was obtained using a method, system and arrangement in accordance with exemplary embodiments of the present invention; and

Figure 4D is a depth-resolved image of the two coins shown in Figure 4C, in which surface features closer to the lens are brighter than those further away; and

Figure 5 is a flow diagram of an exemplary method in accordance with exemplary embodiments of the present invention.

Throughout the figures, the same reference numerals and characters, unless otherwise stated, are used to denote like features, elements, components or portions of the illustrated embodiments. Moreover, while the subject invention will now be described in detail with reference to the figures, it is done so in connection with the illustrative embodiments. It is intended that changes and modifications can be made to the described embodiments without departing from the true scope and spirit of the subject invention as defined by the appended claims.

#### DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS OF INVENTION

A block diagram of a system configured to acquire image data for 3D images in accordance with exemplary embodiments of the present invention is shown

in Figure 1. For example, a light source 100 or other source of electro-magnetic radiation can be provided (which may generate a light or other electro-magnetic radiation that has a broad bandwidth such as, e.g., a titanium-sapphire laser) which may be coupled to an input port of, e.g., a single-mode fiber optic 50/50 splitter 110 or another type of optical splitter. A compact lens-grating arrangement may be provided that can include a lens 120 (e.g., a lens having  $f = 40$  mm and a beam diameter of 0.5 mm) adapted to focus a beam of light, and a transmission grating 130 having, e.g., 1000 lines/mm (Holographix LLC) to diffract the beam and form a spectrally-encoded line (along an x-axis) on a surface of a sample 140. A galvanometric optical scanner 150 can be provided for, e.g., slow scanning of the line along a y-axis.

This exemplary system can provide a spatial transverse resolution of, e.g., approximately 80 microns. The image may include 80 transverse resolvable points, with each transverse spot capable of being illuminated using a bandwidth of, e.g., 1.9 nm. The overall power provided to the sample may be about 4 mW. A double-pass rapidly-scanning optical delay ("RSOD") 160 can be used to control a group delay of the reference arm light. The RSOD 160 may be scanned over a distance of about 1.5 mm at a rate of about 1000 scans per second. An interference signal can be recorded as a function of time by a detector 170, and then demodulated and displayed in real time using a computer 180.

Spatial resolutions and ranging depth measurements and visualization can be improved according to the exemplary embodiments of the present invention by using, for example, a broader bandwidth source and an extended-range optical delay line. Such arrangements are described, e.g., in K. K. M. B. D. Silva, A. V. Zvyagin, and D. D. Sampson, "Extended range, rapid scanning optical delay line for biomedical interferometric imaging," *Elec. Lett.* 35, 1404 (1999).

An illustration of an exemplary technique according to the present invention for encoding both transverse and depth dimensions using broad-spectrum illumination is shown in Figure 2. For example, a sample 200 can include three discrete scattering points in an x-z plane. An interference signal 210 that may be recorded as a function of time by scanning the sample 200 can contain three interference traces 220. Each interference trace can represent depth information

which may be characterized by a corresponding delay,  $\Delta t_i = \Delta z_i / v_g$ , where  $\Delta z_i$  is a depth location of a corresponding scatterer and  $v_g$  is a group-delay velocity. A transverse location can correspond to a carrier frequency,  $2v_p/\lambda_i$ , where  $v_p$  can represent a phase velocity and  $\lambda_i$  may be a wavelength corresponding to the location of scatterer  $i$ . (For example, in the sample containing three scatterers shown in Figure 2,  $i = 1$  to 3.)

The width of each trace,  $T_i$ , can determine a depth resolution, and may be expressed as  $T_i = 0.44 N_x \lambda_i^2 / (v_g \Delta \lambda)$ , where  $\Delta \lambda$  represents a total bandwidth and  $N_x$  is a number of resolvable points along the spectrally-encoded line. A two-dimensional data set 230 (corresponding to locations in x- and z-axes) can be obtained by applying a short-time Fourier transform ("STFT") to the interference data 220 using a Gaussian window centered at  $\Delta t_i$  and having a width of  $T_i$ . The frequency distribution corresponding to a given delay  $\Delta t_i$  can provide spatial information at a corresponding depth,  $\Delta z_i$ .

Alternatively or additionally, a depth-integrated transverse image can be obtained by applying a frequency transform to part or all of a set of interference data simultaneously, or by summing individual depth-resolved images. The frequency transform may be, e.g., a Fourier transform, a short-time Fourier transform, or a Wigner transform. Volumetric data can be obtained by scanning the spectrally encoded line transversely across the sample 200.

The exemplary detection technique according to the present invention described herein can be analogous to a technique which may be used in conventional optical coherence tomography ("OCT"). Conventional OCT techniques are described, e.g., in D. Huang et al., Science 254, 1178 (1991). Exemplary OCT techniques can utilize a broadband light source to obtain a high resolution in an axial direction which may be, e.g., less than about 10  $\mu\text{m}$ . To perform three-dimensional imaging using the conventional OCT techniques, a probe beam should be scanned in two dimensions, which can require a fast beam-scanning mechanism. In contrast, spectrally-encoded endoscopy techniques can utilize a spectral bandwidth to obtain both transverse and axial resolution simultaneously, which may thereby utilize only one slow-axis scan to acquire three-dimensional data sets. Using a given source



bandwidth, the two-dimensional resolution can be achieved with a decreased axial resolution.

- If an exemplary shot-noise limited detection technique is utilized and a source having a uniformly flat spectrum is used, a signal-to-noise ratio ("SNR") associated with a spatial point having a reflectivity  $R$  can be expressed as:

$$SNR = \frac{2 \frac{P_r}{N_x} R \frac{P_s}{N_x}}{2 h \nu P_r B} = \frac{2 R P_s \tau}{h \nu N_x^2 N_z},$$

- where  $P_r$  denotes a total reference arm power,  $P_s$  denotes a total sample power,  $\tau$  represents a line scan period,  $B$  denotes a sampling bandwidth, which may be written as  $B = N_z/2\tau$ , and  $N_z$  indicates a number of axial resolvable points. The expression for the SNR above can be inversely proportional to the square of the number of transverse resolvable points, since only a fraction of the reference arm power (i.e.,  $P_r/N_x$ ) interferes with light returning from a single transverse location.

- Exemplary images of a fingertip acquired using an exemplary 3D spectrally-encoded technique in accordance with certain exemplary embodiments of the present invention are shown in Figures 3A and 3B. The frame size of these exemplary images is approximately 15 x 9 mm). Three-dimensional image data was obtained at a rate of 2.5 frames per second. Each frame in the images of Figures 3A and 3B includes a resolution of 200 points (along a spatially scanned axis) x 80 points (along a wavelength-encoded axis) x 10 points (indicating depth within the sample). The depth resolution was approximately 145  $\mu\text{m}$ .

- For example, a two-dimensional (depth-integrated) image 300 of Figure 3A can be obtained by acquiring about 4000 points per scan, and applying a Fourier transform to these data. Each scan can be divided into about ten time windows that may be transformed separately to extract three-dimensional information. The three-dimensional data can also be presented as a contour map 310 as shown in Figure 3B. Further, a false-color image can be generated and superimposed onto a two-dimensional image to provide an additional three-dimensional visualization.

- In biological tissues, a single-scattered signal emerging from a particular depth within a tissue sample can have a significantly lower intensity than a signal scattered from near the tissue surface. Based on this characteristic of scattered

signals, it is likely that the largest frequency component of each STFT may correspond to a surface height or depth within the tissue.

Three-dimensional image data can be obtained from the samples having a depth range larger than, e.g., the 1.5 mm depth provided directly by the RSOD 160 shown in Figure 1. A greater range of depths can be resolved by obtaining two or more volumetric data sets, where each set can be acquired using a different reference arm path length.

In exemplary embodiments of the present invention, certain components of the system may be provided in a small size in the form of a probe that can be introduced into a body. For example, the lens-grating arrangement and/or the scanning mechanism may be provided in a capsule or other enclosure or housing that can be included with or introduced into a body using a catheter and/or an endoscope. A waveguide can be used to direct at least part of the radiation generated by the light source to the lens-grating arrangement, the reference, and/or the sample. The waveguide can include, for example, a single-mode optical fiber, a multi-mode optical fiber, and/or a multiple-clad optical fiber.

As an example of this extended range acquisition, the surface of a dime placed about 2.4 mm in front of a quarter dollar coin was imaged as shown in Figures 4A-4D using a method, arrangement and system in accordance with certain exemplary embodiments of the present invention. For example, a lens having an  $f$  value of 65 mm was used to provide a larger field of view and depth of focus. Two volumetric data sets were obtained by calculating the STFT for each of two locations of the RSOD double-pass mirror. Each set of image data included 200 horizontal lines, captured at a rate of 5 volume sets per second, and was processed and displayed on a computer screen at a rate of 2.5 frames per second.

Images of the two coins shown in Figures 4A-4D are provided under various conditions. A first image 400 in Figure 4A includes a scale bar having a length of 1 mm, which also corresponds to the images shown in Figures 4B-4D. Although the surfaces of both imaged coins are within the focal depth of the lens, the dime is not seen in the first image 400 of Figure 4A because of the limited scanning range of the RSOD. After adjusting the optical path length of the reference arm by

stepping the RSOD 160 double pass mirror of Figure 1 by 2.4 mm, the surface of the dime can be visualized, as shown in a second image 410 in Figure 4B.

The two volumetric data sets used to form the first and second images 400, 410 can be combined to obtain a depth-integrated two-dimensional third image 420 of Figure 4C and an extended-range depth resolved fourth image 430 of Figure 4D. The surface height in the resolved fourth image 430 can be represented by a gray scale lookup table, where depth locations closer to the lens have higher pixel intensity. Thus, the image of the dime appears brighter, whereas recesses in the lower quarter dollar coin appear the darkest in this image. Other exemplary image processing techniques may be used to provide additional displays of the three-dimensional image data obtained using the exemplary methods and systems described herein.

An exemplary flow diagram of a method 500 according to exemplary embodiments of the present invention is shown in Figure 5. A particular radiation can be provided that can include a first and a second electro-magnetic radiation (step 510). The particular radiation can be provided by, e.g., a broadband light source or a laser. The radiation can include a plurality of wavelengths that are provided simultaneously, or it can optionally can include one or more wavelengths that vary in time. The first and second radiations can be provided, e.g., by directing the particular radiation through an optical arrangement such as a beam splitter.

A spectrally disperse line of radiation can be generated that is associated with the first radiation (step 520). This line can be generated, e.g., by directing the first radiation through a lens-grating arrangement which can include, for example, a diffraction grating and a lens that can be configured to focus and/or direct the first radiation. The spectrally disperse line can be generated all at once or, alternatively, different portions of the line can be generated sequentially when using a light source having at least one wavelength that varies with time.

The spectrally disperse line can be directed toward a portion of a sample to be imaged (step 530). The line may also be scanned in a direction that can be approximately perpendicular to the line (step 540) using an arrangement such as, e.g., a galvanometric optical scanner or the like, which can provide coverage of a region of the sample to be imaged.

The second radiation can be directed to an optical delay arrangement (step 550) or other arrangement such as, e.g., a RSOD, which is capable of affecting the second radiation in a controlled time-dependent manner. A signal associated with the first and second radiations may then be detected (step 560). This signal can be, e.g., an interference which can be obtained by combining the second radiation (after it has been directed to the optical delay arrangement) and electro-magnetic radiation generated by an interaction between the first radiation and a portion of the sample being imaged (step 570). Three-dimensional image data can then be generated that is associated with the signal using a processing arrangement or computer. The data can be generated, e.g., by applying a Fourier transform to the signal and/or demodulating the signal. One or more images can then be displayed using the image data (step 580). Optionally, the image can be displayed in real time.

The foregoing merely illustrates the principles of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. Indeed, the arrangements, systems and methods according to the exemplary embodiments of the present invention can be used with any OCT system, OFDI system, SD-OCT system or other imaging systems, and for example with those described in International Patent Application PCT/US2004/029148, filed September 8, 2004, U.S. Patent Application No. 11/266,779, filed November 2, 2005, and U.S. Patent Application No. 10/501,276, filed July 9, 2004, the disclosures of which are incorporated by reference herein in their entireties. It will thus be appreciated that those skilled in the art will be able to devise numerous systems, arrangements and methods which, although not explicitly shown or described herein, embody the principles of the invention and are thus within the spirit and scope of the present invention. In addition, to the extent that the prior art knowledge has not been explicitly incorporated by reference herein above, it is explicitly being incorporated herein in its entirety. All publications referenced herein above are incorporated herein by reference in their entireties.

WHAT IS CLAIMED IS:

1. A system comprising:
  - at least one first arrangement configured to provide a particular  
5 radiation which includes at least one first electro-magnetic radiation directed to at least one sample and at least one second electro-magnetic radiation directed to a reference arrangement, wherein at least one of the at least one first radiation or the at least one second radiation comprises a plurality of wavelengths, and wherein the at least one first arrangement is configured to spectrally disperse the at least one first  
10 electro-magnetic radiation along at least one portion of the at least one sample; and
    - at least one second arrangement configured to generate data associated with the at least one first electro-magnetic radiation and the at least one second  
electromagnetic radiation, wherein the data is associated with at least one portion of the at least one sample which is located in a direction that is axial with respect to a  
15 direction of the at least one first electro-magnetic radiation.
2. The system according to claim 1, wherein the reference arrangement comprises an optical delay arrangement.
- 20 3. The system according to claim 2, wherein the optical delay arrangement is a rapidly-scanning optical delay.
4. The system according to claim 1, wherein the data is further associated with at least one portion of the at least one sample which is located in a direction that is  
25 transverse with respect to a direction of the at least one first electro-magnetic radiation..
5. The system according to claim 4, wherein the data is further associated with at least one of a two-dimensional image or a three-dimensional image of at least a  
30 portion of the at least one sample.

6. The system according to claim 1, wherein the at least one sample is an anatomical structure.
7. The system according to claim 6, wherein at least a portion of the anatomical structure is provided below a surface of skin.
8. The system according to claim 1, wherein the at least one first arrangement comprises a diffraction grating.
9. The system according to claim 8, wherein the at least one first arrangement further comprises a lens.
10. The system according to claim 9, wherein the at least one first arrangement is further configured to generate a line of radiation on at least a portion of the at least one sample.
11. The system according to claim 10, wherein the at least one first arrangement further comprises at least one scanning arrangement configured to scan the line of radiation in a direction approximately perpendicular to the line.
12. The system according to claim 1, wherein the at least one second arrangement comprises an optical detector.
13. The system according to claim 12, wherein the optical detector includes a charge-couple device.
14. The system according to claim 12, wherein the optical detector is configured to generate a signal based on the at least one first electromagnetic radiation and the at least one second electromagnetic radiation, and wherein the at least one second arrangement is configured to generate a time-frequency transform of the signal.

15. The system according to claim 14, wherein the time-frequency transform is at least one of a Fourier transform, a short-time Fourier transform, or a Wigner transform.
- 5 16. The system according to claim 1, further comprising a processing arrangement configured to provide at least one image based on the data.
17. The system according to claim 16, wherein the at least one processing arrangement is configured to provide the at least one image in real time.
- 10 18. The system according to claim 1, wherein the at least one first electromagnetic radiation is provided through a waveguide arrangement.
19. The system according to claim 18, wherein the waveguide arrangement is at least one of a single-mode optical fiber, a multi-mode optical fiber, or a multiple-clad optical fiber.
- 15 20. The system according to claim 18, wherein the at least one first arrangement is provided in a probe.
- 20 21. The system according to claim 20, wherein the probe comprises at least one of an endoscope or a catheter.
22. A method for generating three-dimensional image data comprising:
- 25 providing a particular radiation which includes at least one first electro-magnetic radiation and at least one second electro-magnetic radiation;
- directing the at least one first electro-magnetic radiation to at least one sample, wherein the at least one first radiation comprises at least one of a plurality of wavelengths and the at least one first electromagnetic radiation is spectrally dispersed
- 30 on the at least one sample;
- directing the at least one second electro-magnetic radiation to a reference arrangement;

detecting a signal associated with the at least one first electro-magnetic radiation and the at least one second electro-magnetic radiation; and

generating image data associated based on the signal, wherein the image data is further associated with at least one portion of the at least one sample which is located in a direction that is axial with respect to a direction of the at least one first electro-magnetic radiation.

23. The method of claim 22, wherein the reference arrangement includes an optical delay arrangement.

24. The method of claim 22, wherein the at least one first electromagnetic radiation is provided in the form of a line, and further comprising scanning the line in a direction approximately perpendicular to the line.

25. The method of claim 22, wherein generating the image data comprises generating a time-frequency transform of the signal.

26. The method of claim 25, wherein the time-frequency transform is at least one of a Fourier transform, a short-time Fourier transform, or a Wigner transform.

27. The method of claim 22, further comprising displaying at least one image based on the image data.

28. The method of claim 27, wherein the at least one image is displayed in real time.



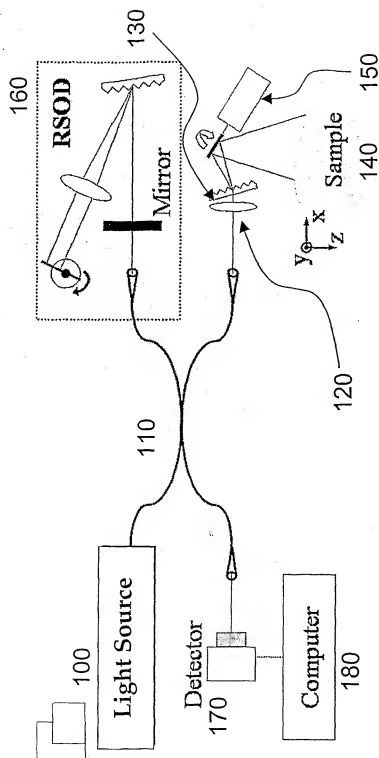


Figure 1

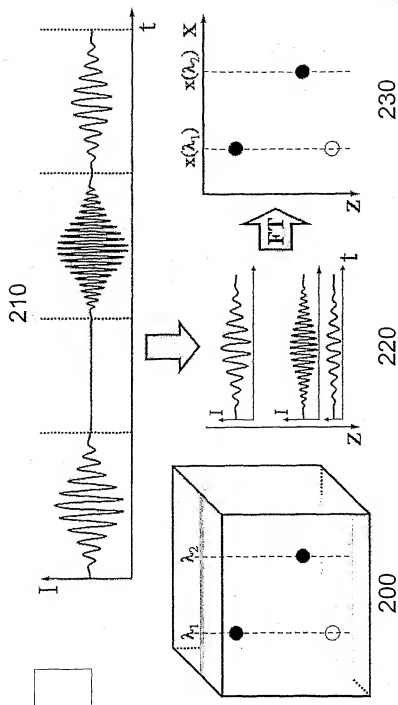


Figure 2

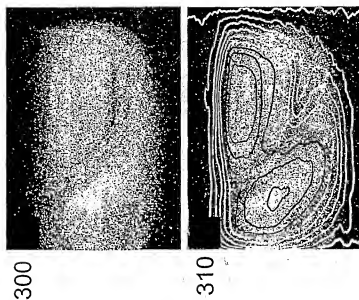


Figure 3

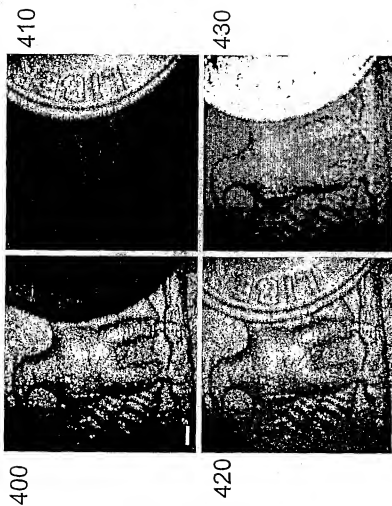


Figure 4

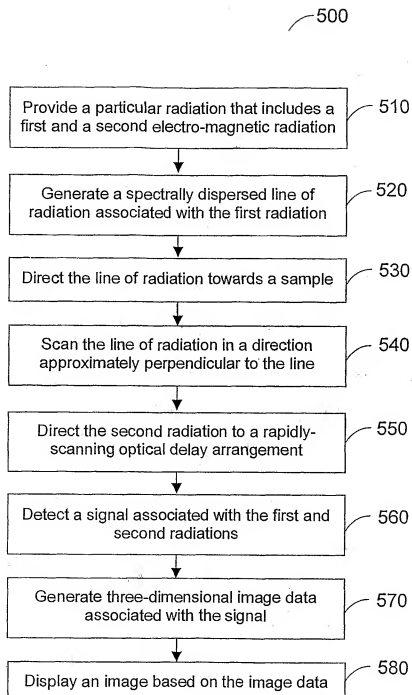


Figure 5



(19) World Intellectual Property Organization  
International Bureau(43) International Publication Date  
7 December 2006 (07.12.2006)

PCT

(10) International Publication Number  
**WO 2006/130797 A3**

## (51) International Patent Classification:

A61B 5/00 (2006.01) G01B 9/02 (2006.01)  
G01N 21/47 (2006.01)

## (21) International Application Number:

PCT/US2006/021343

## (22) International Filing Date: 31 May 2006 (31.05.2006)

## (25) Filing Language: English

## (26) Publication Language: English

## (30) Priority Data:

60/686,518 31 May 2005 (31.05.2005) US

(71) Applicant (for all designated States except US): **THE GENERAL HOSPITAL CORPORATION** [US/US]; 55 Fruit Street, Boston, MA 02114 (US).

## (72) Inventors; and

(75) Inventors/Applicants (for US only): **BOUMA, Brett**, Eugene [US/US]; 12 Monmouth Street, Quincy, MA 02171 (US). **TEARNEY, Guillermo, J.** [US/US]; 12 Fairmont Street, Cambridge, MA 02139 (US). **YELIN, Dvir** [IL/US]; 76 Saint Paul Street, Brookline, MA 02446 (US). **YUN, Seok-hyun** [KR/US]; 30 Cambridge Park Drive, Apt. 4128, Cambridge, MA 02140 (US).(74) Agent: **ABELEV, Gary, DORSEY & WHITNEY LLP**, 250 Park Avenue, New York, NY 10177 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MY, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

## Published:

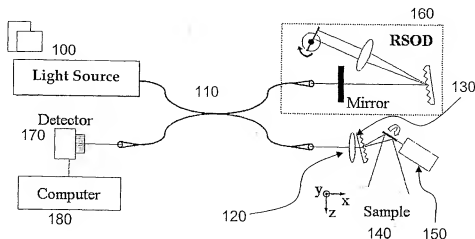
— with international search report

## (88) Date of publication of the international search report:

18 January 2007

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

## (54) Title: SPECTRAL ENCODING HETERODYNE INTERFEROMETRY TECHNIQUES FOR IMAGING



(57) Abstract: Systems, arrangements and methods for obtaining three-dimensional imaging data are provided. For example, a broadband light source (100) can provide a particular radiation. A first Electro-magnetic radiation can be focused and diffracted, and then provided to at least one sample (140) to generate a spectrally encoded line. A second Electro-magnetic radiation may be provided to a reference, which may include a double-pass rapidly-scanning optical delay (160), where the first and second Electro-magnetic radiation's can be based on the particular radiation. An interference between a third Electro-magnetic radiation (associated with the first Electro-magnetic radiation) and a fourth Electro-magnetic radiation (associated with the second Electro-magnetic radiation) can be detected. The spectrally encoded line may be scanned over the sample in a direction approximately perpendicular to the line. Image data containing three-dimensional information can then be obtained based on the interference. The exemplary imaging methods and systems can be used in a small fiber optic or endoscopic probe.

## INTERNATIONAL SEARCH REPORT

International application No  
PCT/US2006/021343

## A. CLASSIFICATION OF SUBJECT MATTER

INV. A61B5/00 G01N21/47 G01B9/02

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B G01N G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99/44089 A (GEN HOSPITAL CORP [US]; WEBB ROBERT H [US]; TEARNEY GUILLERMO J [US]); 2 September 1999 (1999-09-02) page 3, line 10 - page 6, line 6 figures 1,3-5	1-28
P,X	WO 2006/014392 A (GEN HOSPITAL CORP [US]; BOUMA BRETT E [US]; TEARNEY GUILLERMO [US]; YE) 9 February 2006 (2006-02-09) paragraph [0054] figure 5a	1-28
P,X	WO 2005/054780 A (GEN HOSPITAL CORP [US]; YELIN DVIR [US]; BOUMA BRETT E [US]; TEARNEY G) 16 June 2005 (2005-06-16) page 8, line 5 - page 9, line 30 figure 2	1-28

-/-

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

## \* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"S" document member of the same patent family

Date of the actual completion of the international search

20 October 2006

Date of mailing of the international search report

03/11/2006

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Völlinger, Martin



# INTERNATIONAL SEARCH REPORT

International application No

PCT/US2006/021343

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	<p>YELIN D ET AL: "Three-dimensional imaging using spectral encoding heterodyne interferometry" Optics Letters Opt. Soc. America USA, vol. 30, no. 14, 15 July 2005 (2005-07-15), pages 1794-1796, XP002403910 ISSN: 0146-9592 the whole document</p>	1-28
X	<p>YELIN D ET AL: "Three-dimensional spectrally encoded imaging" Optics Letters Opt. Soc. America USA, vol. 28, no. 23, 1 December 2003 (2003-12-01), pages 2321-2323, XP002403911 ISSN: 0146-9592 page 2321, right-hand column, paragraph 1 - page 2322, left-hand column, paragraph 1 figure 1</p>	1-28
A	<p>TEARNEY G J ET AL: "HIGH-SPEED PHASE- AND GROUP-DELAY SCANNING WITH A GRATING-BASED PHASE CONTROL DELAY LINE" OPTICS LETTERS, OSA, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC, US, vol. 22, no. 23, 1 December 1997 (1997-12-01), pages 1811-1813, XP000735869 ISSN: 0146-9592 page 1811, left-hand column, paragraph 1 - page 1812, left-hand column, paragraph 1 figure 1</p>	1-3,22, 23

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2006/021343

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9944089	A	02-09-1999	AU 758078 B2 13-03-2003
		AU 2882399 A 15-09-1999	
		EP 1057063 A1 06-12-2000	
		JP 2002505434 T 19-02-2002	
WO 2006014392	A	09-02-2006	NONE
WO 2005054780	A	16-06-2005	EP 1687587 A1 09-08-2006